# Eddy Current Array Imaging for Additive Manufacturing of Metal Parts

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*San Antonio, TX*

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# Abstract



Qualification of additive manufactured (AM) metal parts is a new challenge facing a range of aerospace stakeholders, from part manufacturers for engines and structures, to platform integrators, to operators such as the U.S. military. The unique designs and material conditions associated with the AM process are driving an increasing need to characterize small defects, material properties, and geometry in-situ (layer-by-layer during the fabrication of complex parts), as well as to perform post-process nondestructive evaluation (NDE). This paper describes new advances in eddy current array sensing for both in-situ sensing during the AM process and for post-process NDE for AM metal parts.

New advances in MWM-Array eddy current technology, including sensors, instrumentation and data analytics are described. AM processes discussed include Laser Powder Bed Fusion (LPBF), Electron Beam Direct Energy Deposition (EB-DED), Blown Powder DED, and Wire Arc AM (WAAM). This presentation will describe the challenges associated with integrating sensors into metal AM machines and the current state-of-the-art for eddy current array in-situ sensing. This presentation will also describe the benefits of MWM-Array technology for post-production inspection of thin wall AM parts and the relatively rough surfaces typical of metal AM parts.

# Agenda



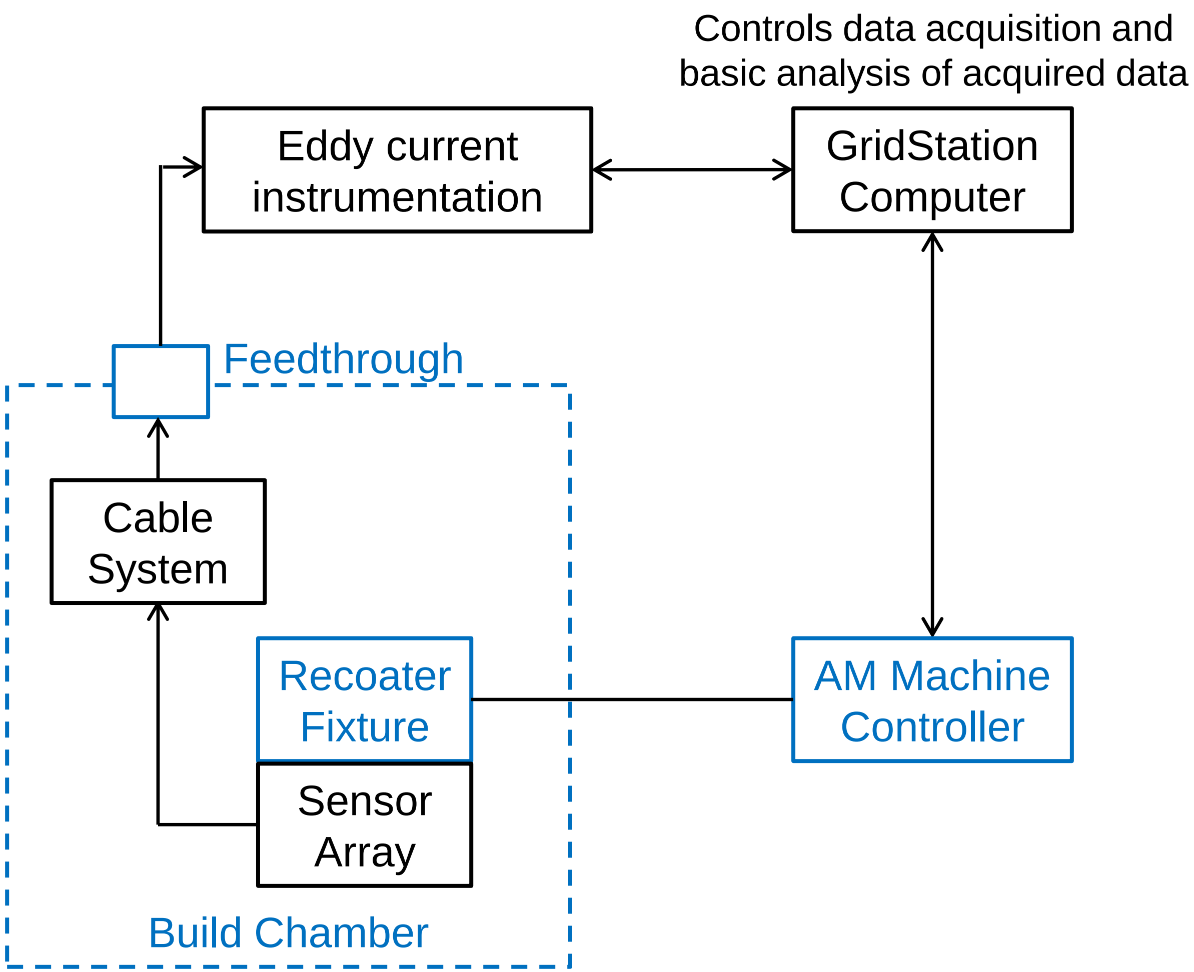
- JENTEK Sensors, Inc. Introduction
  - AM for LPBF introduction
  - Historical success
  - Product roadmap
- JENTEK AM Technology
  - Eddy current arrays with LPBF
  - Simulated results
  - Z-directed filtering
  - Measurement grid approaches
  - Model for powder response

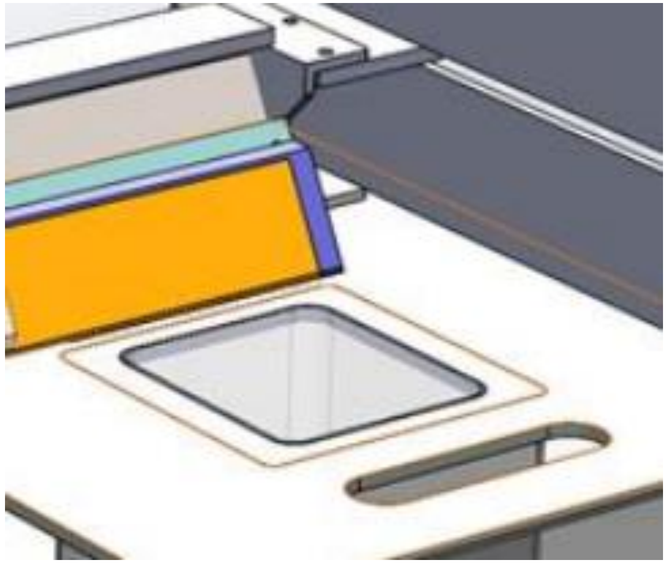
**JENTEK has completed two fully integrated demonstrations on SLM 125 machines with a 79-channel MWM-Array for full width layer-by-layer powder bed imaging.**

# JENTEK Approach for Laser Powder Bed Fusion (LPBF)



Block diagram of basic approach



# JENTEK Sensors, a history of delivering solutions



Outstanding Paper Award,
*ASNT Materials Evaluation Magazine*,
July 2003, Aerospace Health Monitoring

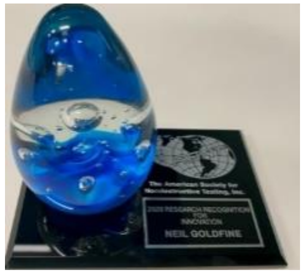
2004 Outstanding Phase III Transition Award, awarded by the Navy Transition Assistance Program



2006 National Tibbetts Award for outstanding contributions to the SBIR Program

2007 FAA/Air Transport Association 2007 "Better Way" Award for Engine Component Inspection Technology

2020
ASNT Innovation Award



Awards

## Success Stories

- **2001-present; fighter aircraft engine blade inspection**
- 2002-present; C-130 propeller inspection
- **2005-present; fighter aircraft disk slot inspection**
- **2007-2011; space shuttle leading edge Inspection**
- **2009; fighter aircraft blade dovetail inspection**
- 2011-present; Rolls Royce AE engine inspection
- 2013-present; SCC crack detection for pipelines
- 2015-present; A380 pump hole inspection
- 2016-present; engine blade fir tree inspection
- **2018-present; additive manufactured part inspection**
- 2019-present; conductivity mapping for AL plate
- **2020-present; friction stir weld inspection**

Sticky solutions that produce a revenue stream over decades

New transitions with >10x revenue growth opportunities

- **Spacecraft weld inspection**
- **Additive manufacturing in-situ sensing**
- **Army asset quality and sustainment**
- NDT for aircraft
- Off-shore NDT
- NDT for automotive in-process

Targeted solutions, continual revenue

https://jenteksensors.com/resourcecenter.php

# Technology Development Roadmap for Core Products



JENTEK focuses on remaining two decades ahead of the competition.
This has accelerated with the launch of new products in the last few years and proven continual improvement capacity.

Handheld jET®

2018 - 2020
Depot and production version

jETi

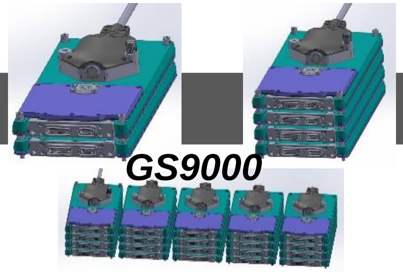
2024-26
Field hardened version

2026
Embedded version

2027
Challenging environment version

GS8200

2018 - 2020
Depot and production version

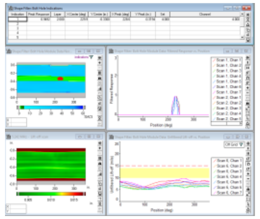


GS9000

2023-25
Backpack portable version

2026
Embedded version

2027
Challenging environment version



GridStation® Software

2021
User-friendly GridStation software

2022-25
Robotic and automation integration

2023-25
Tablet version of GridStation software

2024 - 2027
jAI (augmented intelligence tool set)

Existing Production/Depot

Funded Development for Field & Embedded

2008 - 2017
JENTEK invests in new product lines

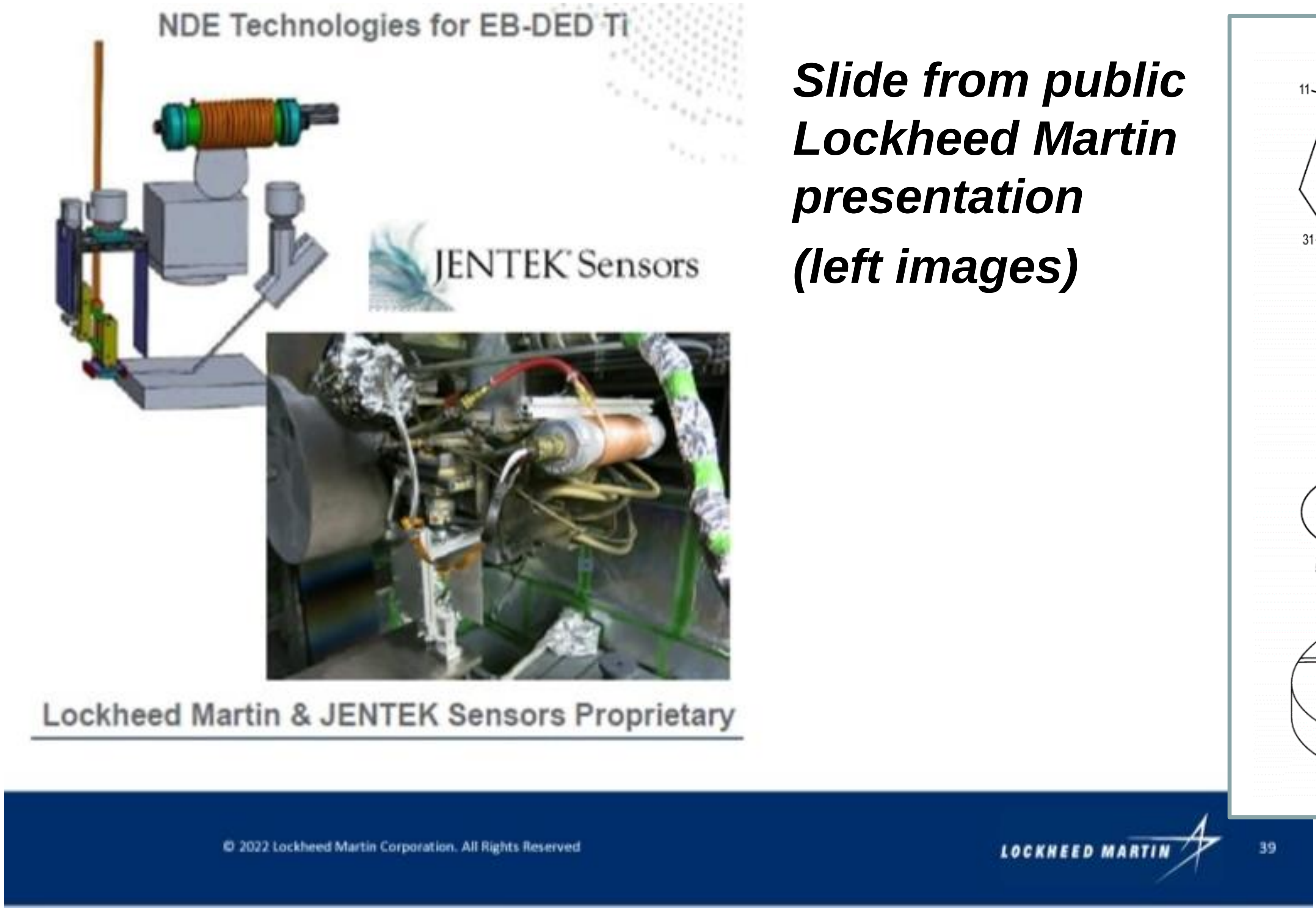
2022 2023 2024 2025 2026 2027

# Backpack Portable Scanning System (GS9000 Version)



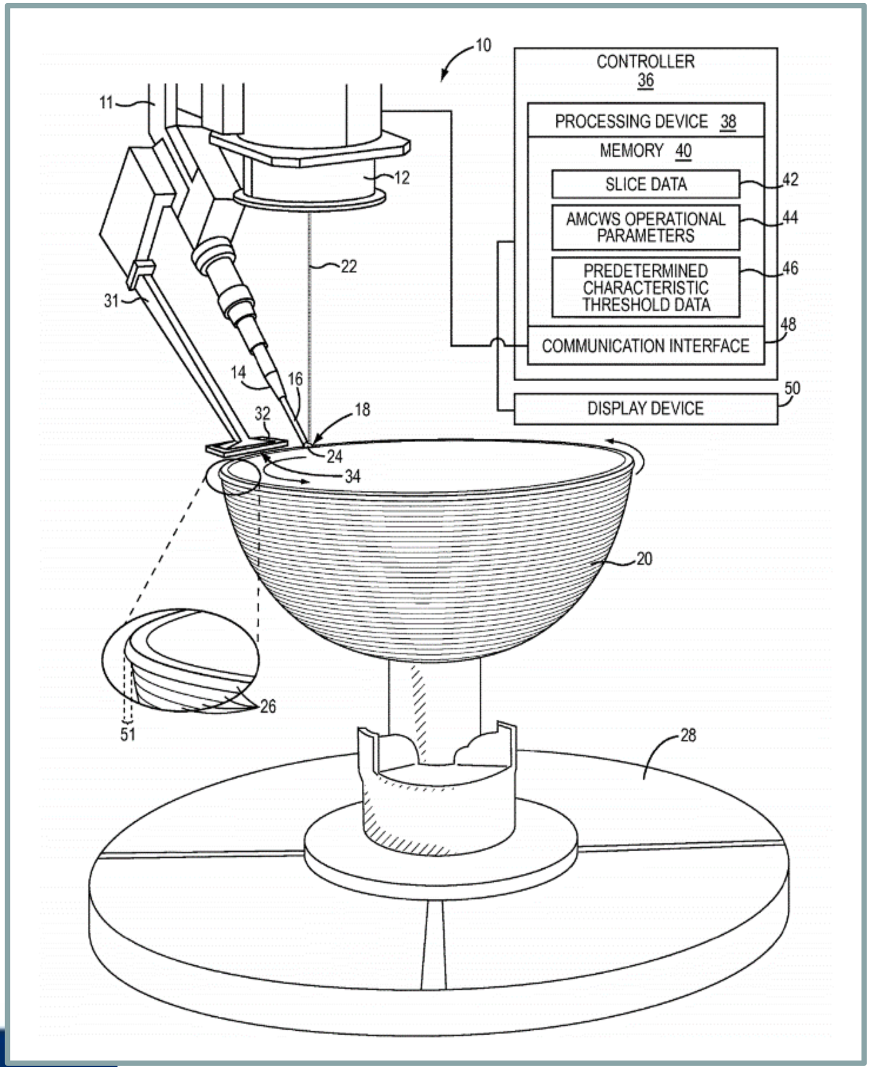
# JENTEK Project for Electron Beam Direct Energy Deposition






***Slide from public Lockheed Martin presentation***

***(left images)***



## Additive Manufactured Component Modeling and In-Process Sensing/NDE, for Qualification and Sustainment


Neil Goldfine, Andrew Washabaugh, Stuart Chaplan, Todd Dunford, Taylor Simon, Matthew Helseth *JENTEK Sensors*

Adam Pilchak, David Furrer
*Pratt & Whitney, Materials & Processes Engineering, East Hartford, CT*

Masoud Anahid, Jingfu Liu, Sergei Burlatsky
*RTX Technology Research Center, East Hartford, CT*

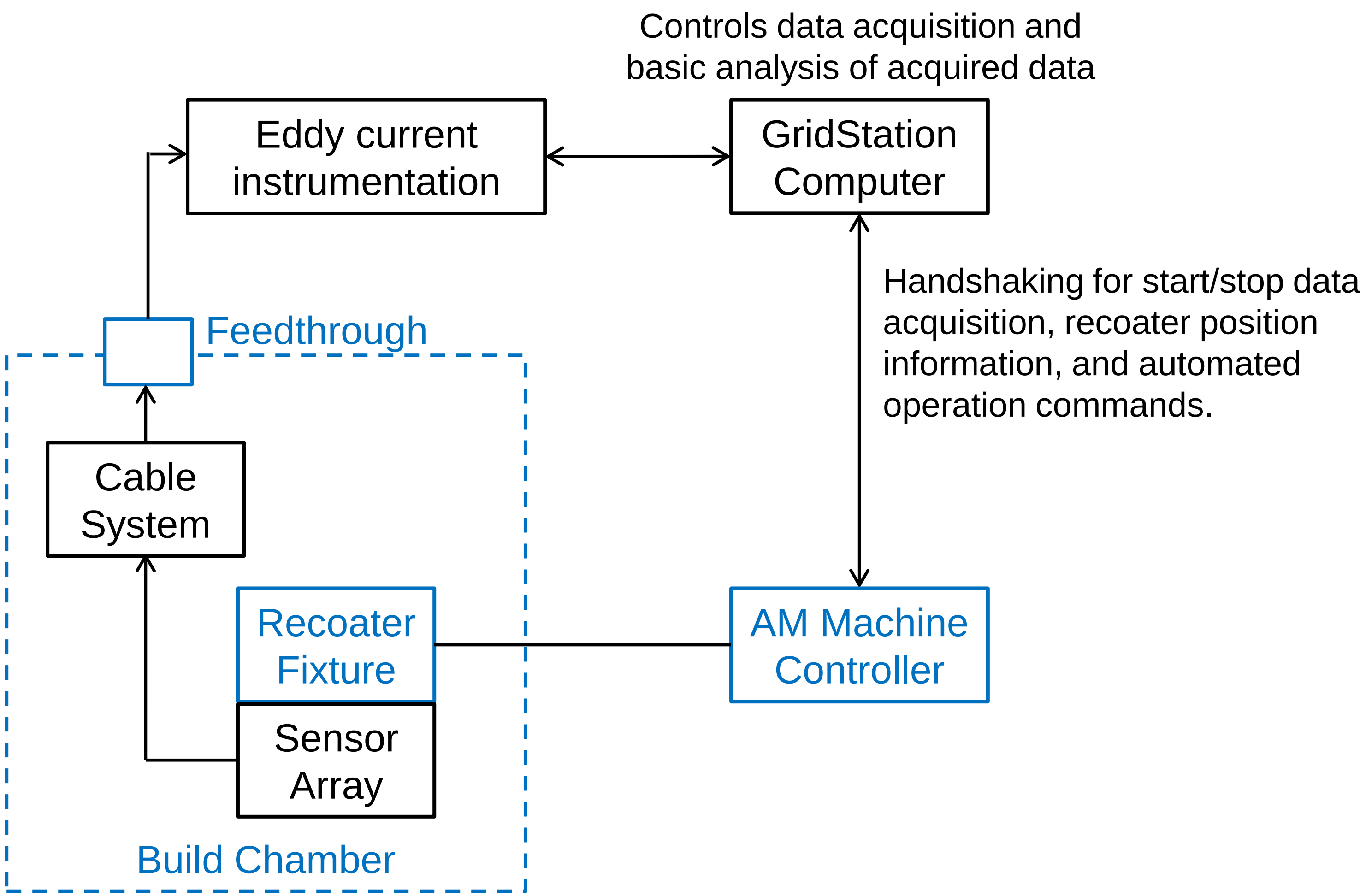


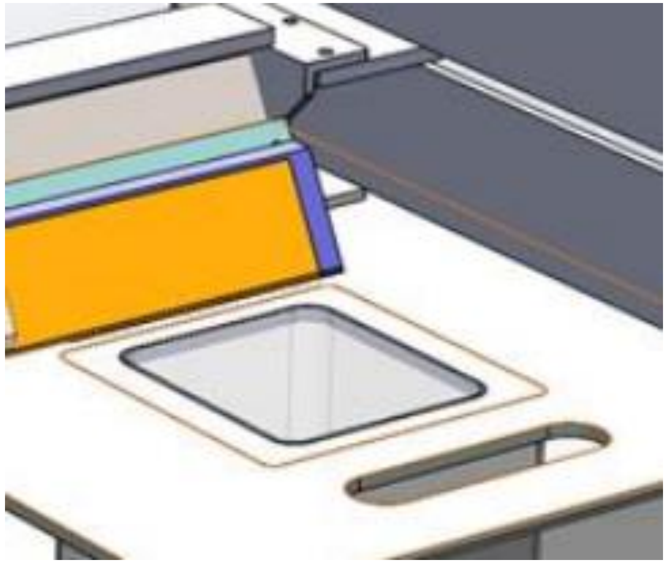
Qualification of Additive Manufactured (AM) components, whether using Laser Powder Bed Fusion (LPBF) or Direct Energy Deposition (DED; including Laser DED, Blown Powder DED, Electron Beam DED, etc.), requires observability of geometric dimensions and material conditions, as well as the detection of relevant defects. Also, within the context of ASIP a plan for in-service inspections and life management is required…

# JENTEK Approach for Laser Powder Bed Fusion (LPBF)



Block diagram of basic approach

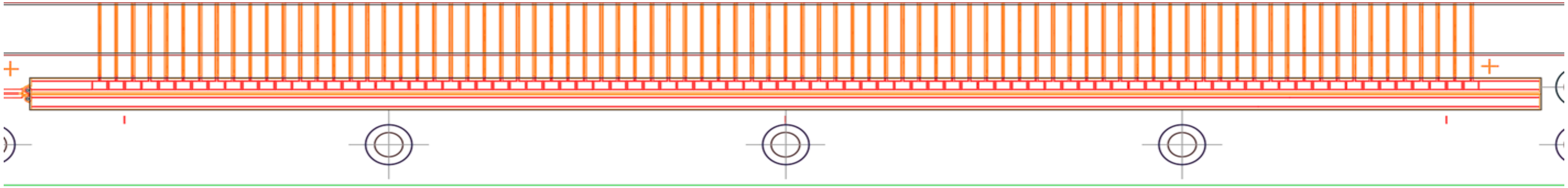


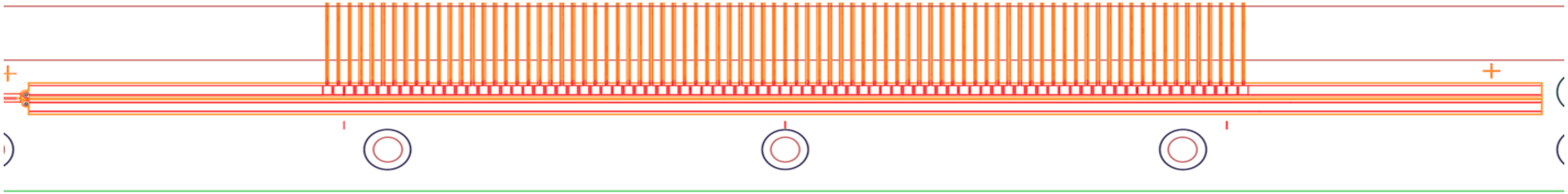
# JENTEK Approach for Laser Powder Bed Fusion (LPBF) [5]



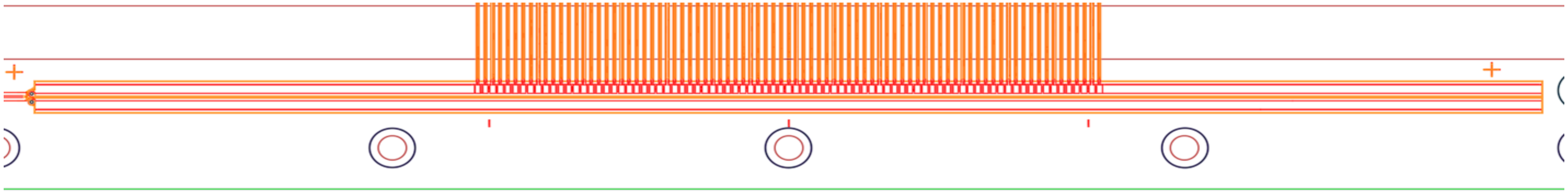
FA332 (for comparison)
1.65 mm sense element spacing
130.0 mm scan width



FA364
1.10 mm sense element spacing
86.9 mm scan width



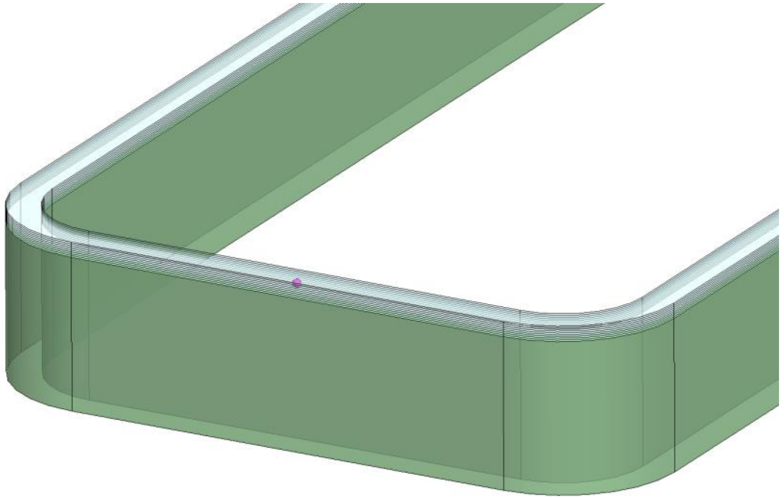
FA366
0.75 mm sense element spacing
59.25 mm scan width



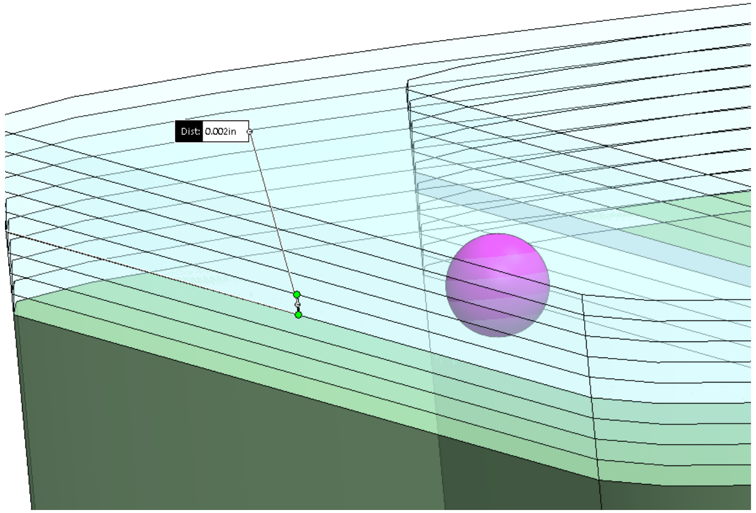
# z-Directed Filtering (1)



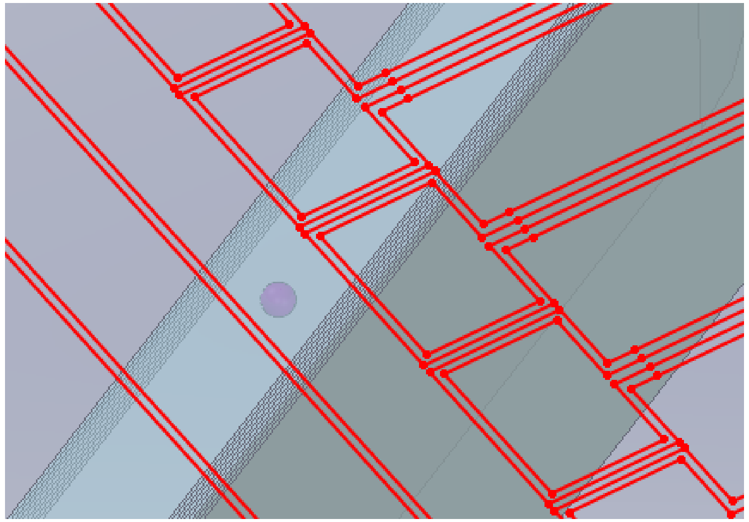
Example of a void (0.25 mm diameter) within a thin wall (1 mm) built-up structure



Expanded view illustrating scans every 50 microns (0.002 in.) so that multiple scans have the opportunity to image the same defect

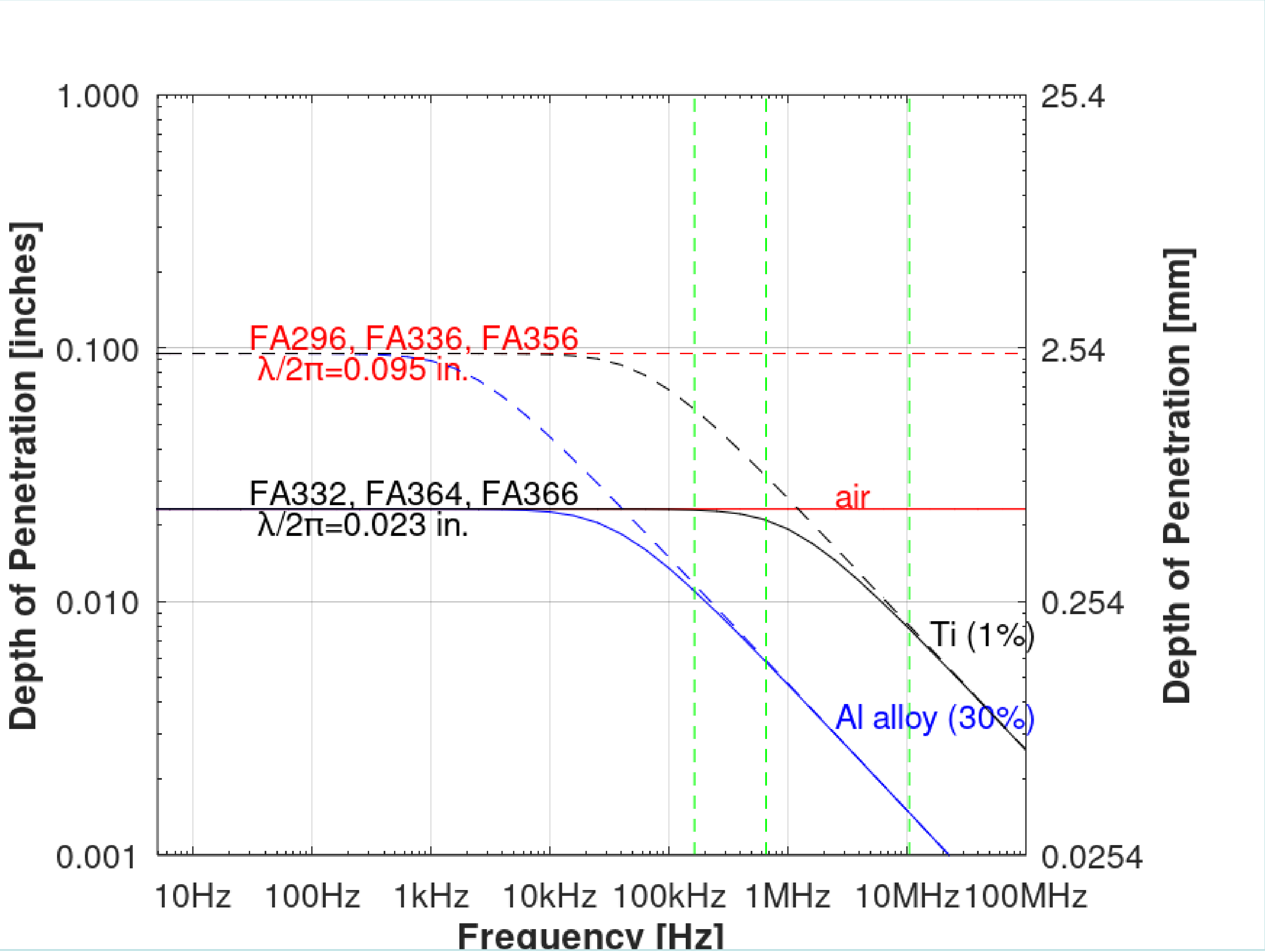



Expanded view showing the sense elements of the FA332 sensor array passing over the built-up material.



# Depth of Penetration

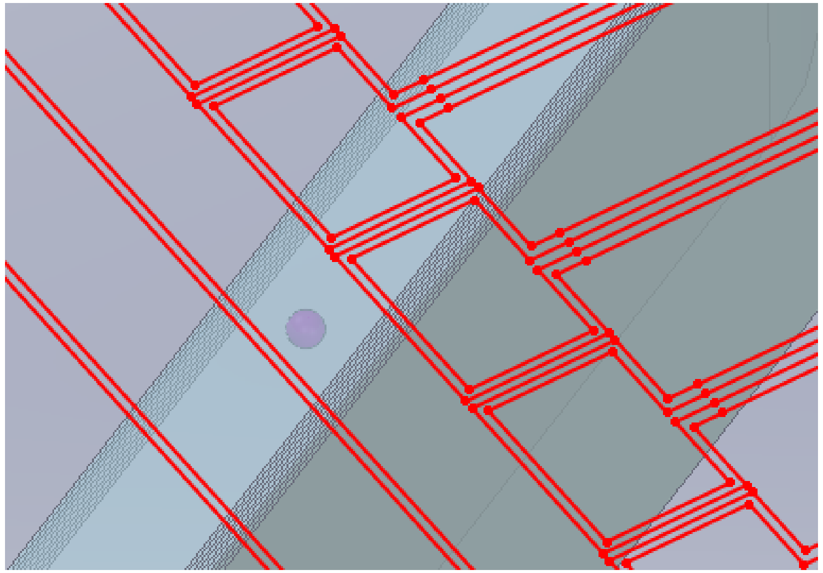





$$DOP = \frac{1}{Re\left(\sqrt{\left(\frac{2\pi}{\lambda}\right)^2 + j\left(\frac{2}{\delta^2}\right)}\right)}$$

$$Low\ Frequency\ Limit = \frac{\lambda}{2\pi}$$

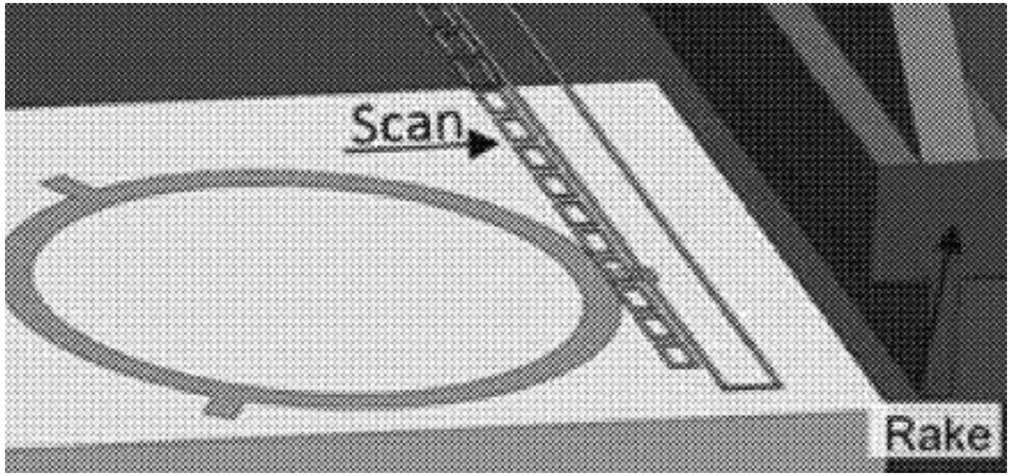
$$Skin\ Depth(\delta) = \sqrt{\frac{1}{\pi f \mu \sigma}}$$

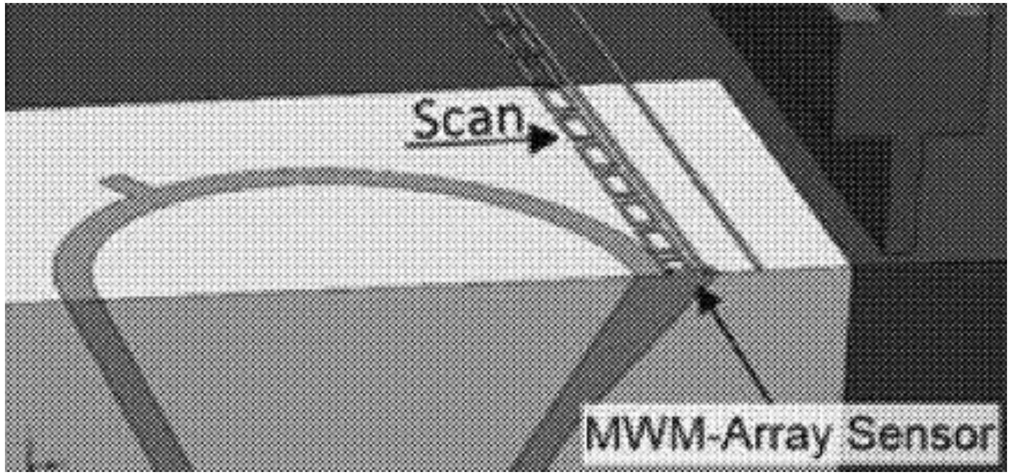


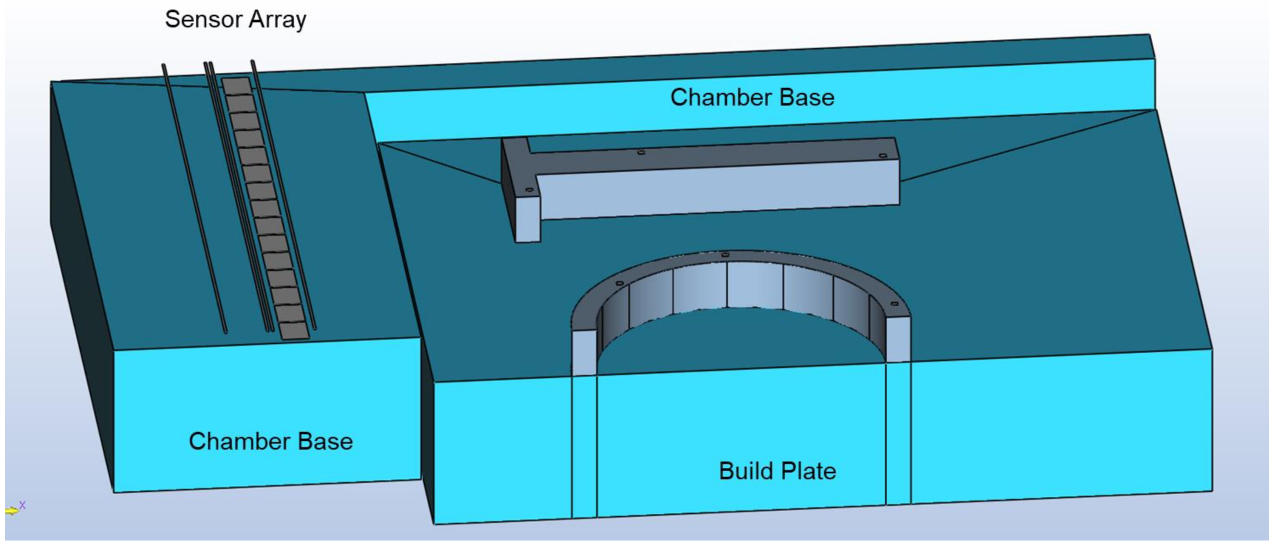
# Simulated response geometry



Simulated responses for array scanned over typical geometries with and without voids

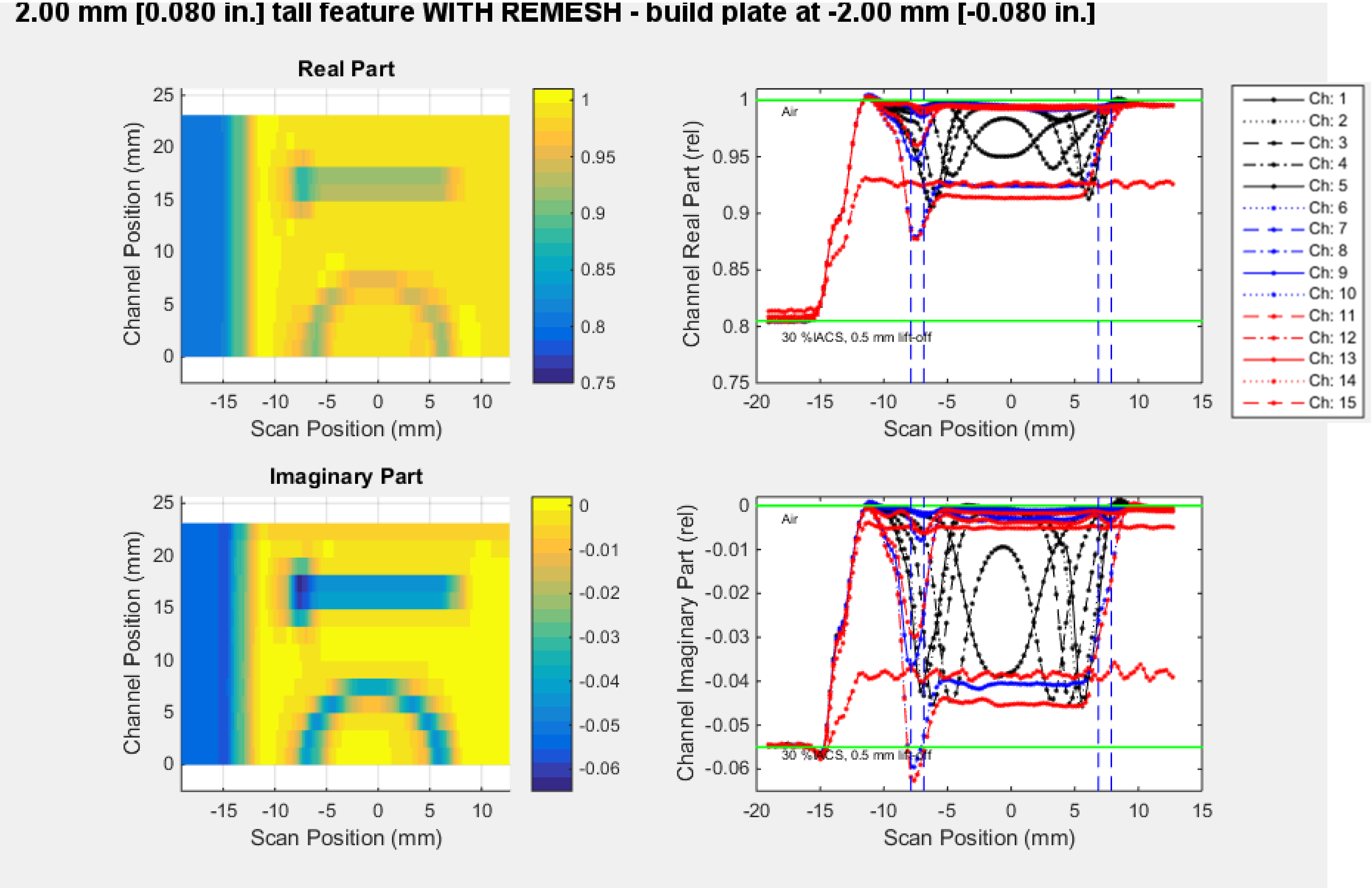


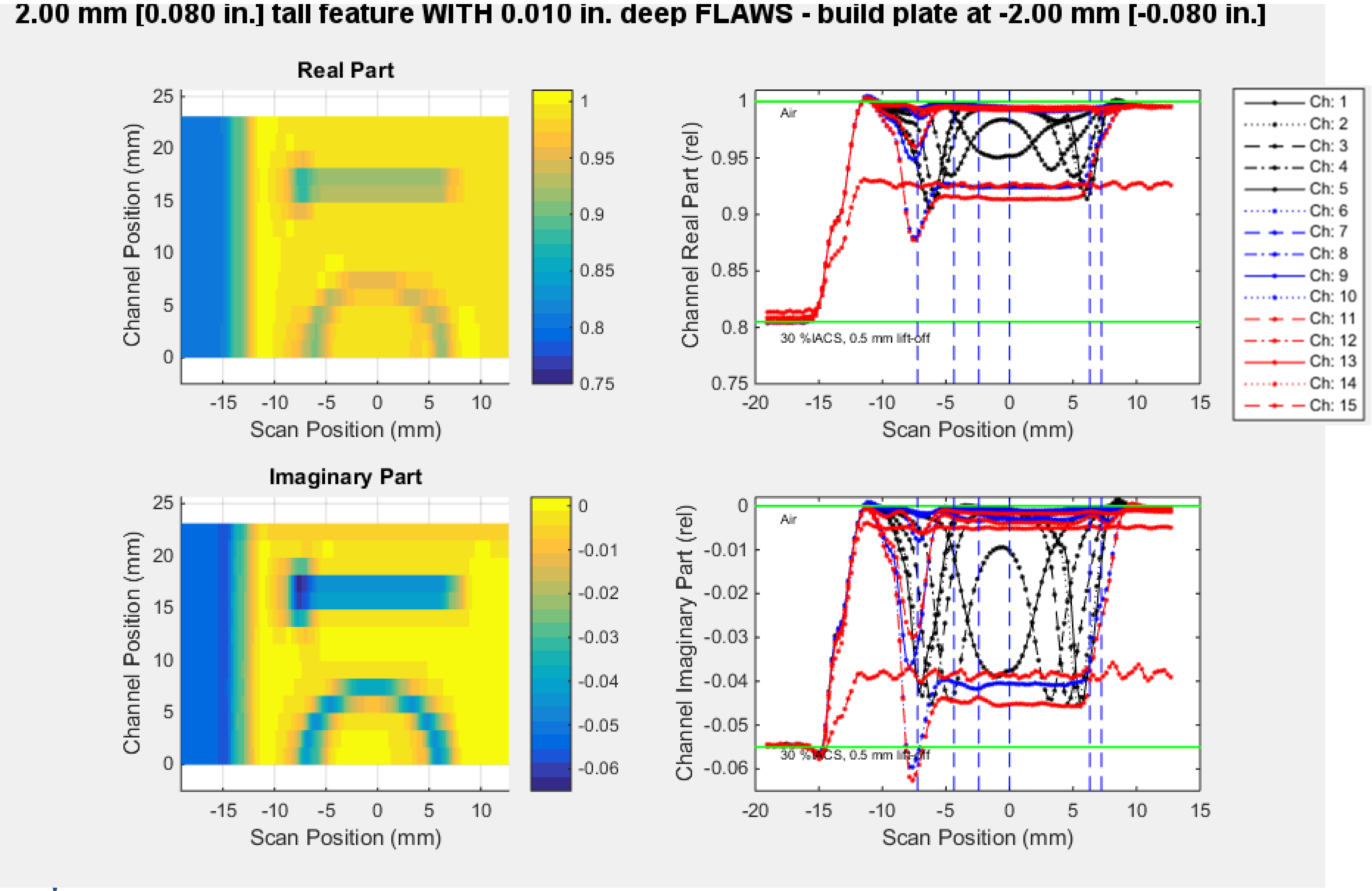
# Simulated response – no flaws





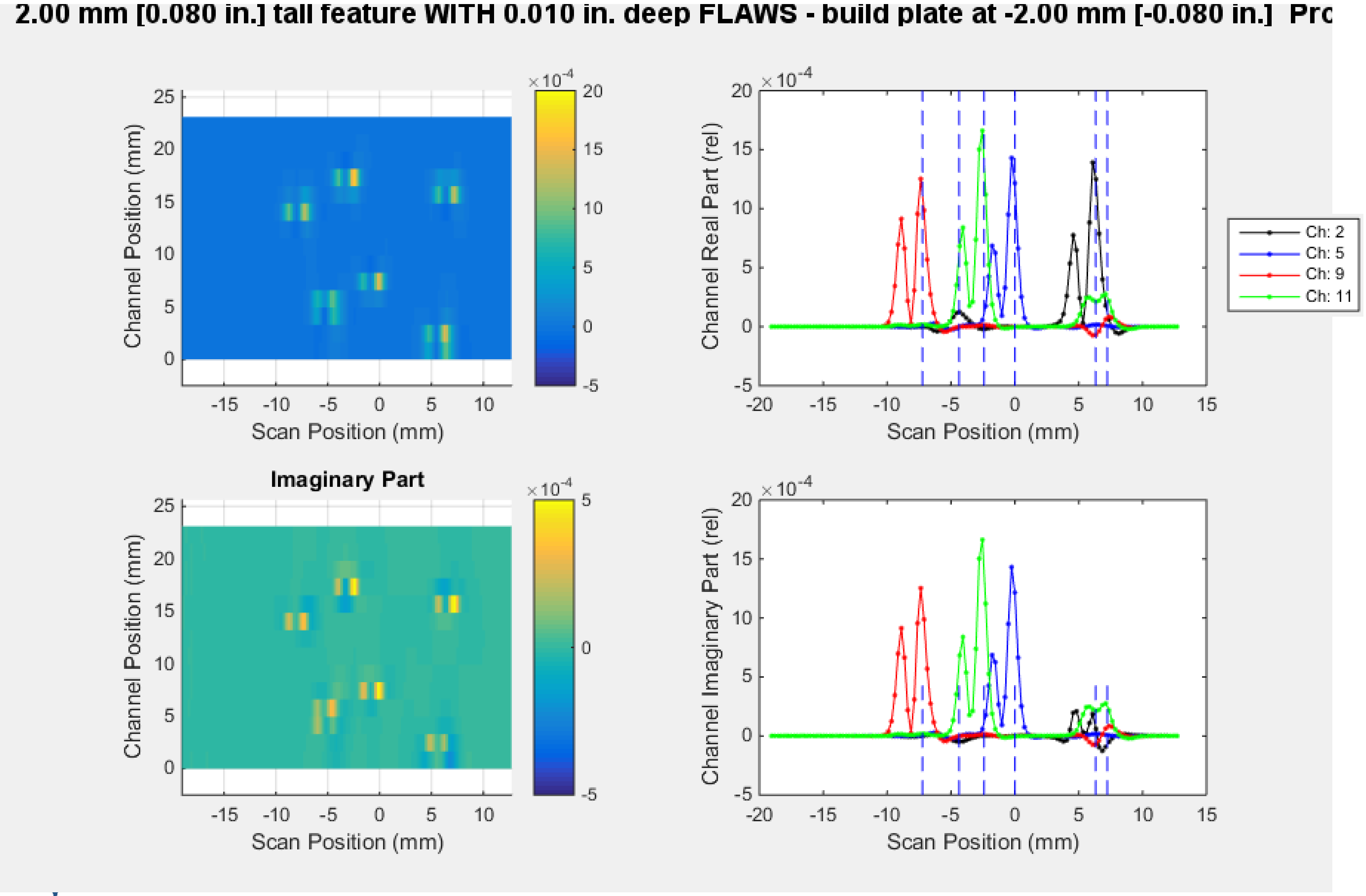
# Simulated response – 0.010 in. flaws





# Simulated response difference

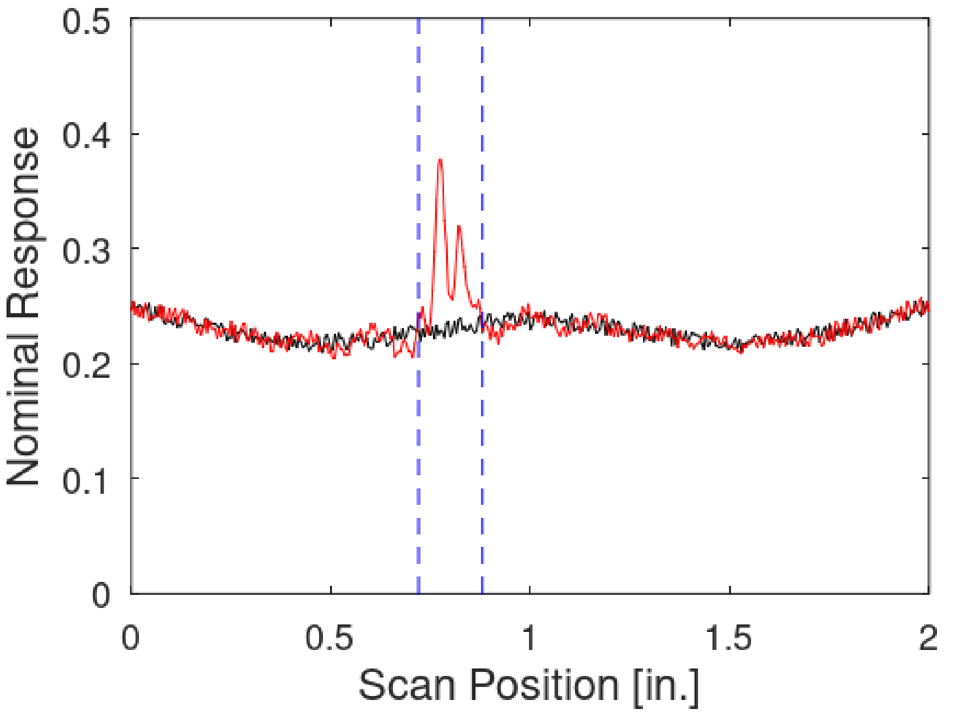




# z-Directed Filtering (2) – simulated responses



Example scan across a solid material with a flaw

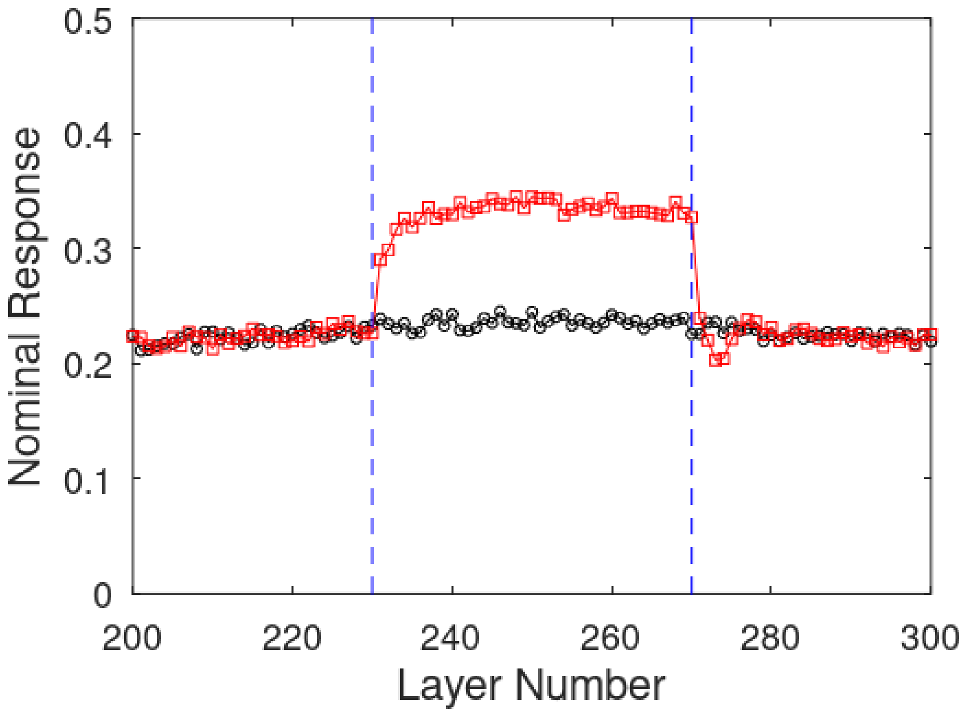



Red line represents a channel passing over a flaw

Black line represents a nearby channel

Responses are typically “noisy” from surface roughness and material property variations

Example layer-by-layer (z-directed) plot




Example response as a void is created then covered; blue lines indicate when void is present in layers.

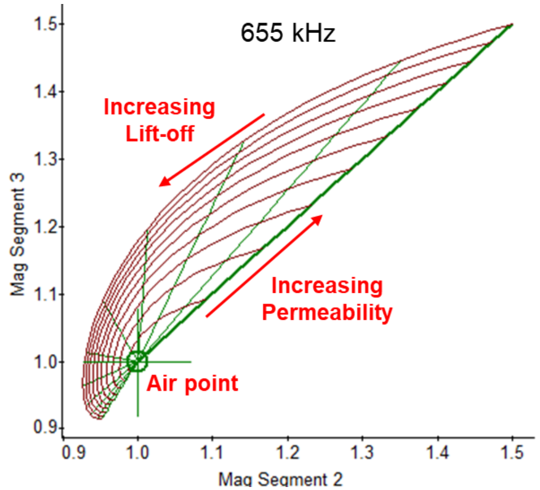
Response to the void increases for several layers then levels off

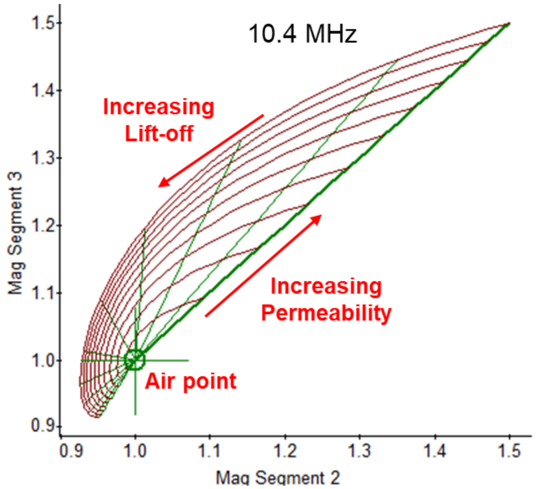
Some sensitivity to subsurface voids through several layers depending upon excitation frequency.

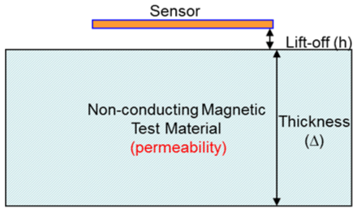
# Measurement Grid Methods (Permeability & Lift-off)



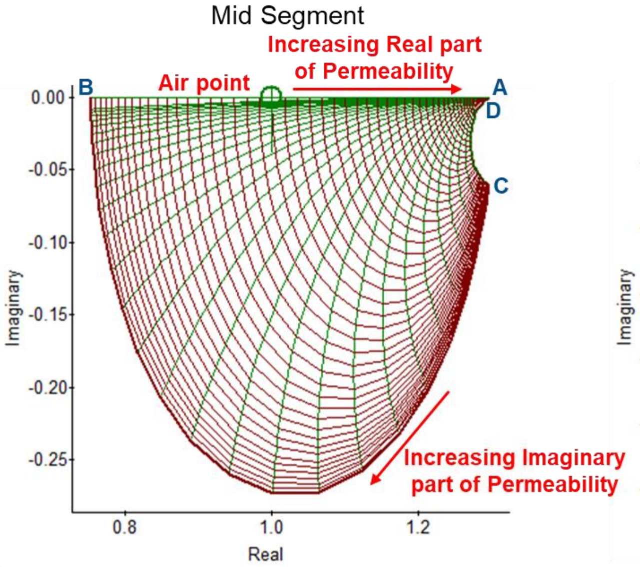
Segmented sensor grids for estimation of permeability and lift-off

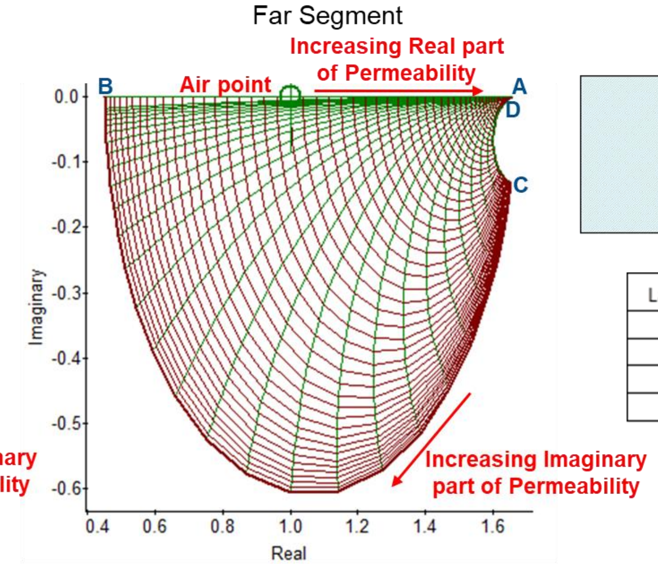


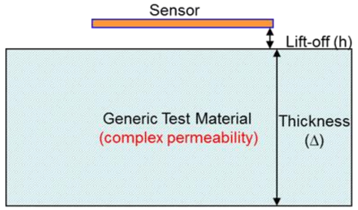




Complex mu – halfspace, 0.020 in. lift-off, FA294



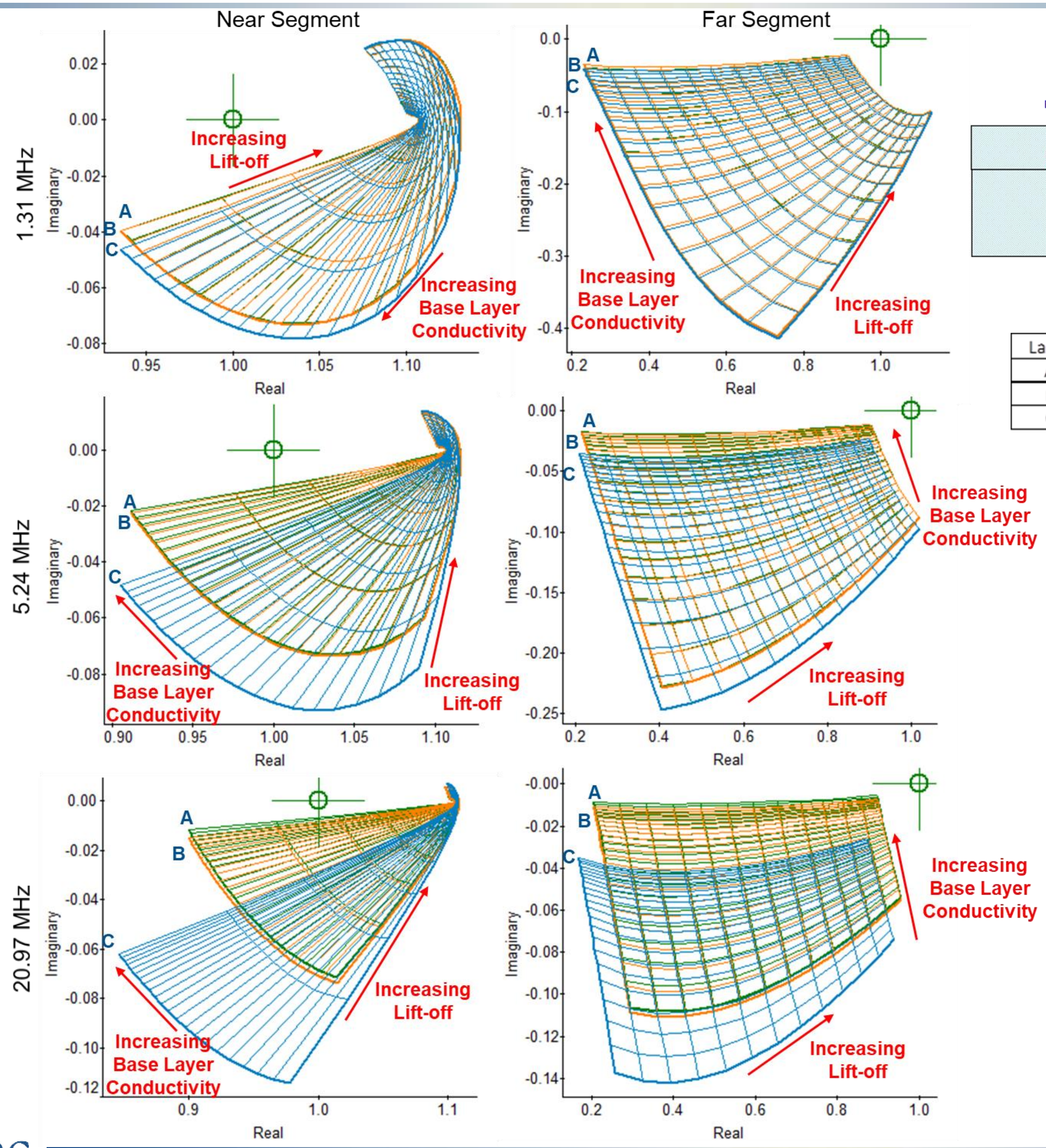



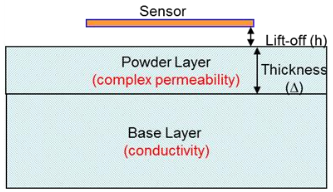




| Label | $\mu_{real}$ | $\mu_{imag}$ |
|---|---|---|
| A | 1000 | 0 |
| B | 0.1 | 0 |
| C | 0.1 | -10 |
| D | 1000 | -10 |

# Measurement Grid Methods (Nonferrous)






| Label | Color | Powder |
|---|---|---|
| A | Green | Air |
| B | Orange | Titanium |
| C | Blue | Aluminum |

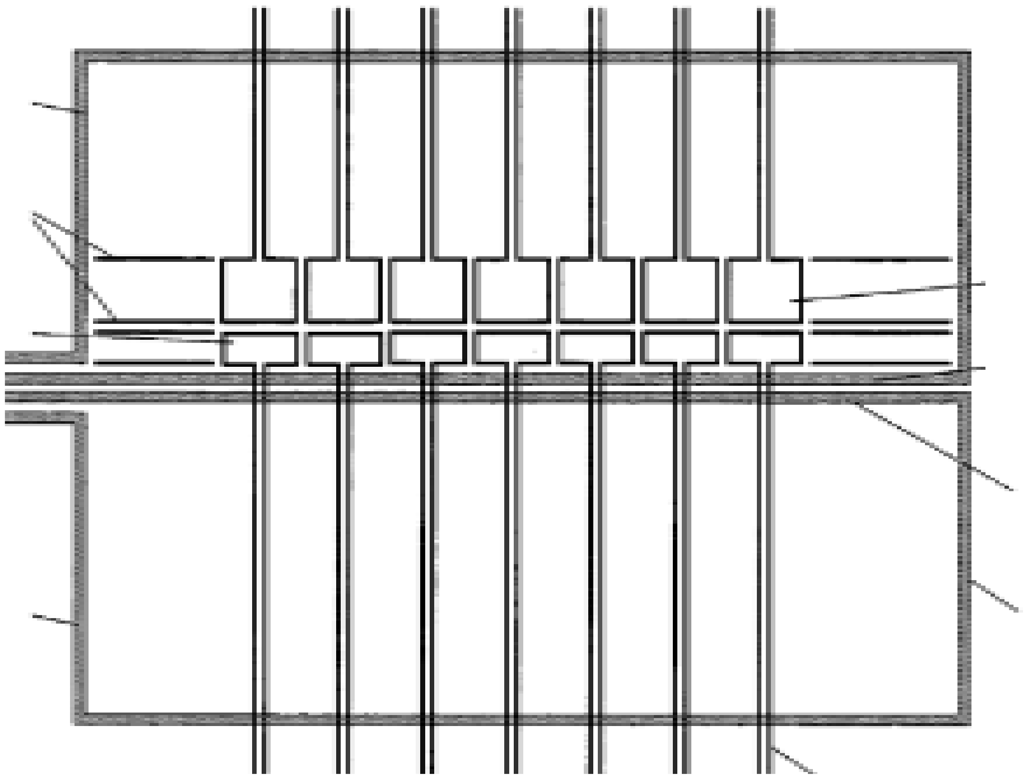
Segmented sensor grids for estimation of base material conductivity through a powder layer

Complementary information between frequencies and segments

# Linear Segmented Field MWM-Array



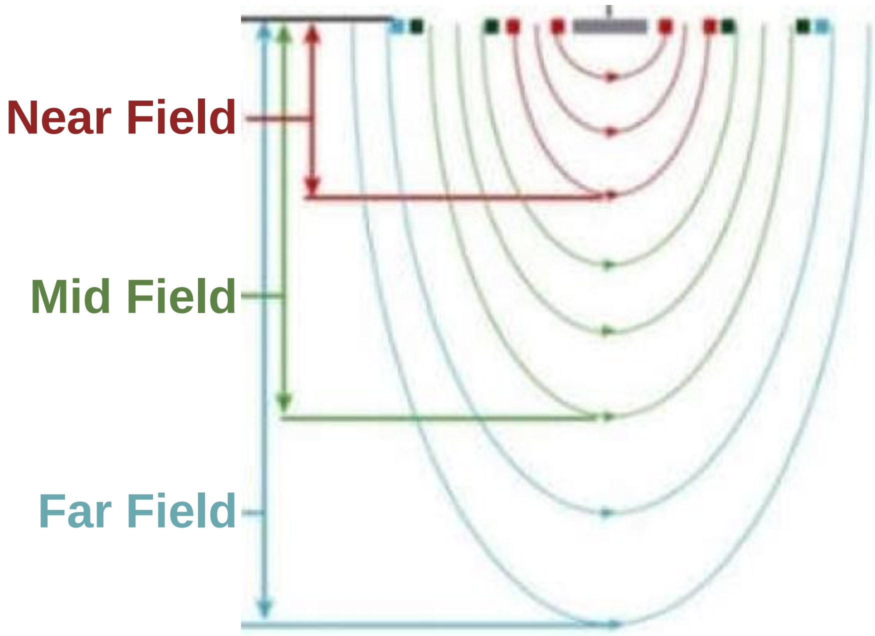
- Segmented Field SF-MWM-Arrays and MWM-Arrays Implementation:
  - Fully parallel sensing
  - 3 frequencies simultaneously
  - Model-Based data analytics
  - High resolution conductivity mapping, layer-by-layer



# Cylindrical Segmented Field – MWM-Rozette

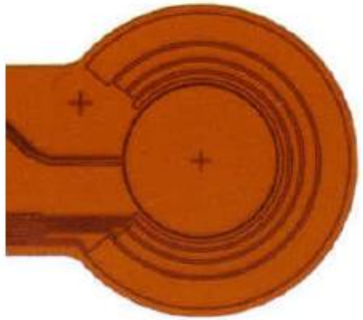


- Sensors designed for elements to respond to components of the sensing field that penetrate to different depths within the test material.



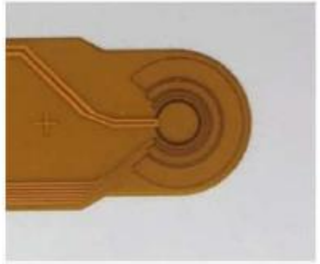

FA246

– Four sense elements
– ~1.0 inch diameter



FA294

– Three sense elements
– ~0.4 inch diameter



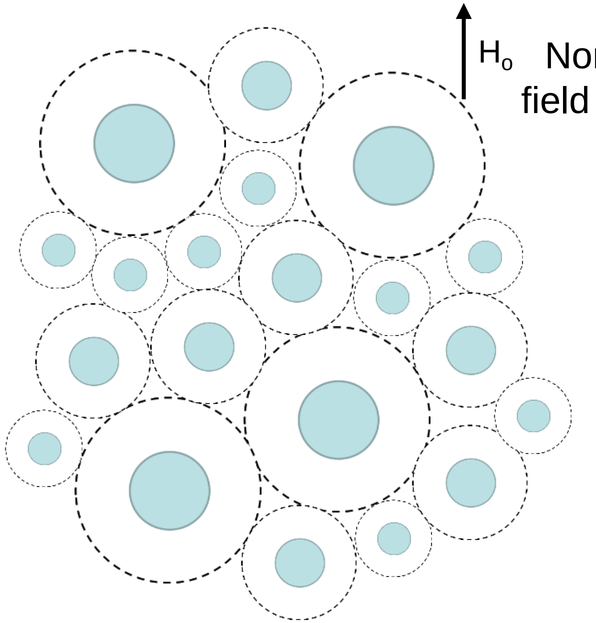
- Segmented Field circular and Linear MWM-Arrays offer advantages for powder characterization but are not required for metal characterization.

# Powder Model (Composite Sphere Assemblage)



- Unpublished eddy current particle model extensions spans low frequency (no eddy currents) to high frequency (thin skin depth compared to particle diameter) regimes

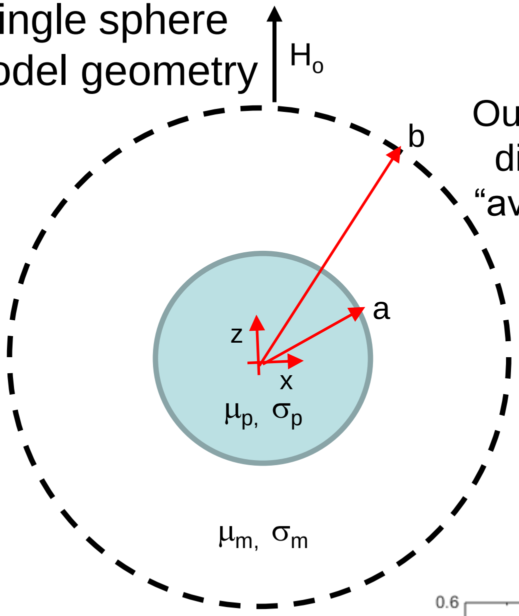
Sphere assemblage




Nominal magnetic field intensity applied by sensor

Simplification for local field calculations

Single sphere model geometry



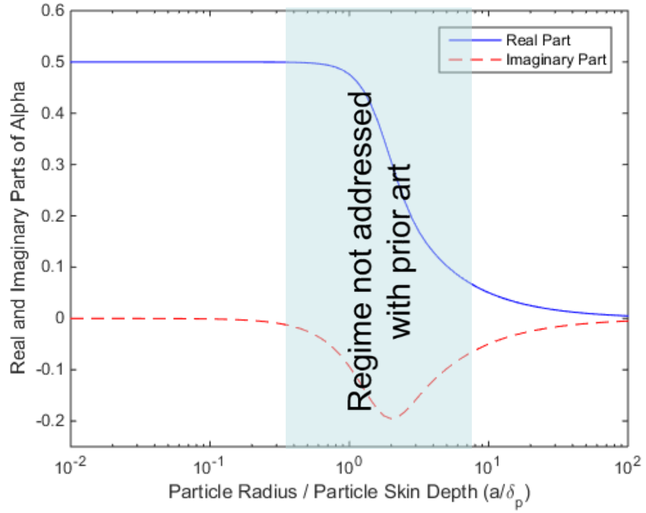

Outside radius provide average distance where field reaches "average" field for each particle

Composite Powder Complex Permeability

$$\frac{\mu^*}{\mu_o} = \frac{\mu_o(1 - v_p) + \mu_p\ \alpha(1 + 2v_p)}{\mu_o(1 + v_p/2) + \mu_p\ \alpha(1 - v_p)}$$

$$\alpha = \frac{I_{3/2}(ka)}{kaI_{1/2}(ka) - I_{3/2}(ka)}$$

$$k^2 = j\omega\mu\sigma = 2j/\delta^2$$

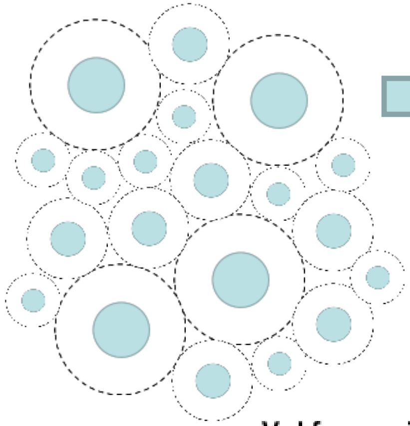


# Powder Model – Example Predicted Responses



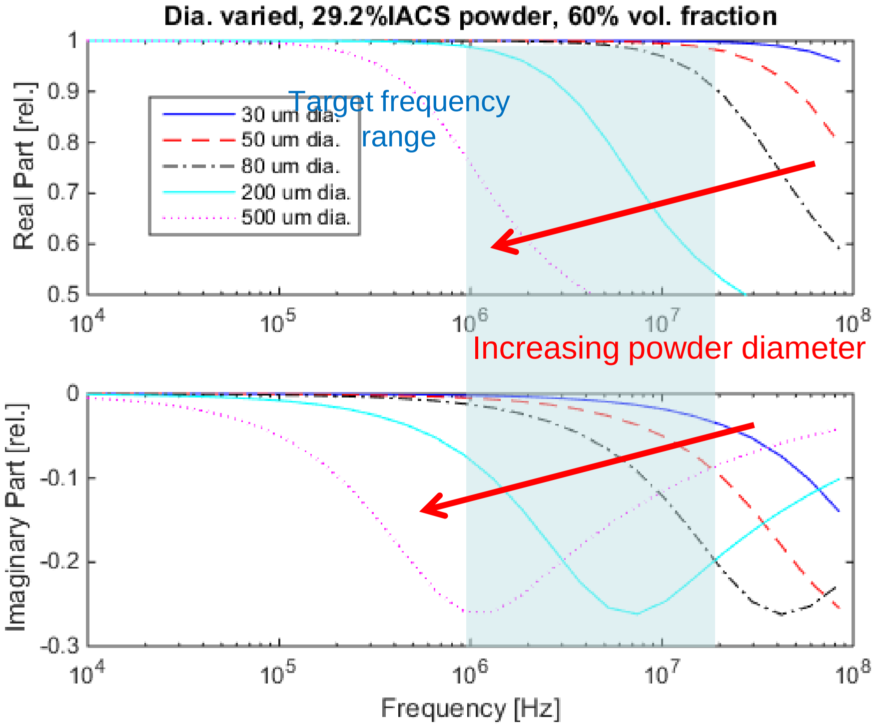
- New powder effective material property model exercised
- For target diameters of 30-100 um, frequencies of 1-20 MHz should be reasonable
  - Imaginary part of permeability shows powder responses at lower frequencies
  - Higher frequencies would be better for lower conductivity or smaller diameter powders

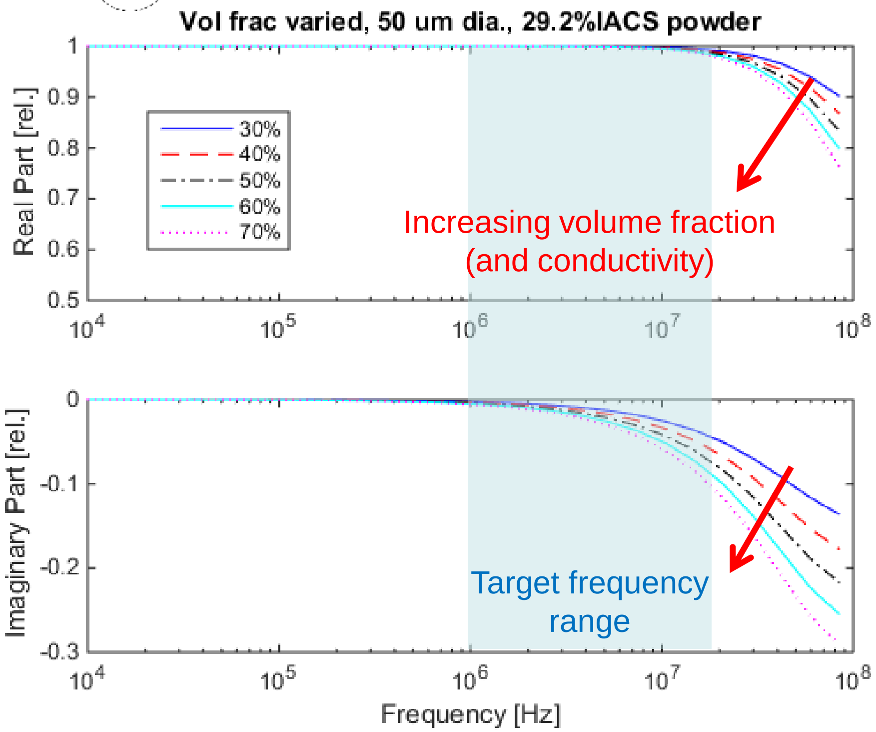
Sphere assemblage



Layered Media Geometry


Powder diameter, conductivity, and volume fraction represented as real and imaginary parts of relative permeability in layer model



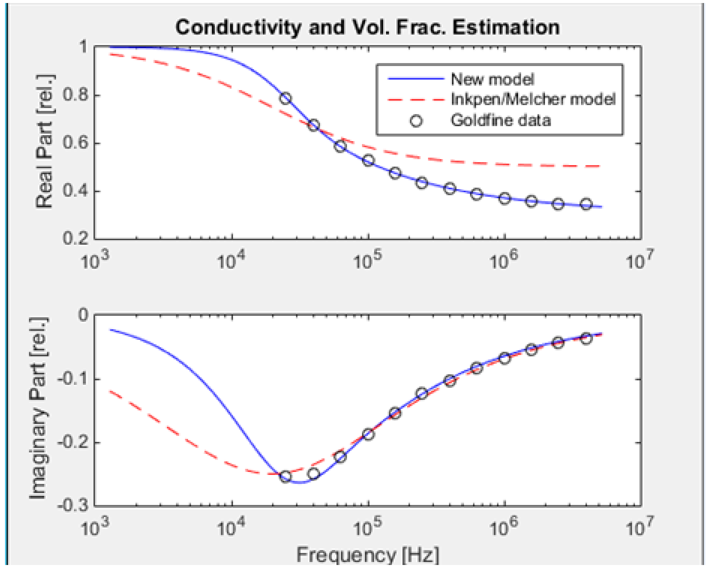



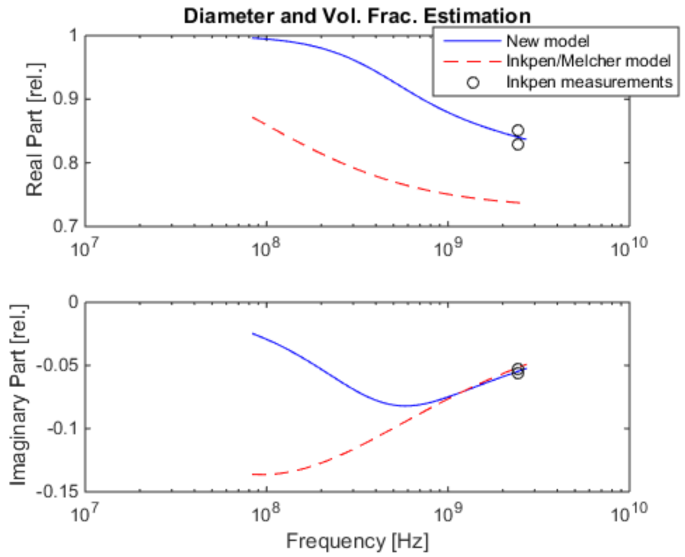
# Powder Model – Historical Data Results



- Goldfine aluminum granule data, assumed Diameter = 2 mm, Conductivity = 34.5 %IACS, Volume Fraction = 0.4
- Inkpen/Melcher data microwave data on Al particles
  - Diameter = 16.4 micron average (8.2 micron average radius) (measured)
  - Conductivity = 60.0 %IACS (particle conductivity assumed based on model analysis)
  - Volume Fraction = 0.2 or 0.217 (assumed values used for model analysis)
  - Assumed a particle diameter of 24 microns (12 micron radius) to get better fit to data
- Inkpen/Melcher (high frequency) model only fits part of the data, not both real and imaginary parts
- New model provides good fit to both real and imaginary parts of permeability
- Good estimate of volume fraction but particle radius and conductivity were not estimated independently
  - Note that pure aluminum has a conductivity of 65.5 %IACS and alloys have a lower conductivity

Estimated Properties:
Conductivity = 63.8 %IACS
Volume Fraction = 0.604




Estimated Properties:
Diameter = 0.0164 mm
Volume Fraction = 0.163

# Summary



JENTEK AM Technology for LPBF

- Eddy current arrays with parallel electronics
  - Full coverage of powder bed, with 79 channel modules
  - Layer-by-layer, with simultaneous three frequency eddy current sensing
  - Fully parallel electronics (all sensing elements simultaneously)
  - Air calibration (ASTM 2338)
  - Non-contact with automatic rescaling for variable liftoff
  - Sensing independent of sensor temperature
- Z-directed filtering using model-based inverse methods and high-fidelity impedance data
- Teaming with modeling and implementation partners

**JENTEK has completed two fully integrated demonstrations on SLM 125 machines with a 79-channel MWM-Array for full width layer-by-layer powder bed imaging.**